

# OBSERVATIONS OF THE DYNAMICS AND ACOUSTICS OF ATTACHED CAVITIES

S. L. Ceccio and C. E. Brennen  
California Institute of Technology  
Pasadena, California

## Abstract

In this study of attached cavities on an axisymmetric headform, measurements were made of the noise generated by the cavitation. In addition to hydrophone recordings, a new technique employing flush mounted electrodes was used to measure the steady state and dynamic volume fluctuations of the attached cavities. The spectra of the noise are quite featureless and show some decrease in the high frequency content as the cavities become larger. However, the spectra from the electrode measurement show some distinct frequencies of fluctuation.

## 1. Introduction

This paper presents some measurements of the dynamics and acoustics of attached cavities. Information regarding the dynamics of this kind of cavitation is important in a number of different applications. As discussed by Weitendorf [1989] it is critical to the understanding of ship propeller/hull interactions. It is also of importance to the understanding of the acoustic signal generated by ship propellers (Blake et. al. [1977]) and the dynamic behavior of cavitating pumps (Brennen and Acosta [1976]). The dynamics of attached cavities have been difficult to study due to the absence of simple, non-intrusive volume measurement techniques. Presented here are the initial results of a new method to study both the steady state and dynamic volume fluctuations of attached cavities, using electrical impedance measurements between flush-mounted electrodes. The same hardware has been used recently to study bubble cavitation (Brennen and Ceccio [1989]). In the present study the technique is used to provide a measurement of the cavity volume fluctuations. In other contexts, the electrodes could be used on either steady or moving surfaces as well as on surfaces which are geometrically complex.

## 2. Nomenclature

$D$  = diameter of the axisymmetric body  
 $E$  = electrode signal voltage  
 $F$  = electrode spectral coefficient  
 $H$  = acoustic spectral coefficients  
 $L$  = cavity Length  
 $P$  = free stream pressure  
 $P_v$  = water vapor pressure  
 $Re$  = Reynolds number based on the diameter  $Re = UD/\nu$   
 $s$  = streamwise coordinate measured along the body surface from at the stagnation point.  
 $U$  = free stream velocity  
 $\nu$  = kinematic viscosity of water  
 $\rho$  = density of water  
 $\sigma$  = cavitation number,  $(P - P_v)/(\frac{1}{2}U^2)$

## 3. Experimental Methods

Attached cavities were produced on an axisymmetric headform; the body used was a Schiebe headform with a 5.14 mm maximum diameter and a minimum pressure coefficient of -0.75 (Gates et al. [1979]). The actual final diameter of the body, denoted by  $D$ , is 5.08 mm due to truncation. The body was constructed of lucite and was instrumented with three surface electrodes made of silver epoxy and located at positions  $s/D = 0.608, 0.645, \text{ and } 0.691$ . The surfaces of the body, including the electrode surface and electrode-lucite interface were highly polished. The interior of the headform contained water and a ITC-1042 hydrophone (Fig. 1). The acoustic impedance of lucite and water are nearly matched, thus reducing the attenuation due to reflection on the body surface. With this hydrophone geometry, external flow noise was reduced, and the dispersive effects of free stream bubbles were minimized.

The headforms were supported by a two bladed sting with a nominally zero degree yaw angle.

The experiments were conducted in the Caltech Low Turbulence Water Tunnel (Gates [1977]). In all the tests, the velocity of the tunnel was maintained constant and the pressure slowly reduced to approach the final operating point. The controlled air content of the water was 6-7 ppm for the results presented here.

Flash photographs of the attached cavities were taken for each operating point. The examples shown in Fig. 2 are for a tunnel velocity of 9 m/s and cavitation numbers of 0.40, 0.38, 0.36, and 0.34. The approximate percentage of the body circumference covered by the cavity (or cavities) can be measured from these photographs in addition to the mean cavity length and thickness. Various cavity surface structures such as surface waves and cavity "fingering" may also be seen.

The internal hydrophone detected the noise made by the cavities. The signal was amplified and low pass filtered with a cut off of 100 kHz and digitized at a sampling rate of 1 MHz. The high frequency content of the signal is limited by the response of the hydrophone, which is flat to approximately 80 kHz. Furthermore, the entire noise measurement is strongly affected by reverberation in the tunnel, especially in the frequency range up to 5 kHz where the fundamental acoustic modes of the tunnel are located. By placing the hydrophone inside of the bluff body, the signal to noise ratio was significantly improved, and the effect of free stream bubbles on the acoustic signal was reduced.

The electrodes were used to measure both the mean volume and the volume fluctuations of the attached cavities. An alternating potential is applied to each electrode with the center electrode voltage being 180 degrees out of phase with the others. Changes in the center electrode current are detected and recorded. When a void is present over a portion of an electrode, two separate effects may change the signal. First, the percentage of the surface area of the electrode which will freely conduct electricity is reduced, and hence the current de-

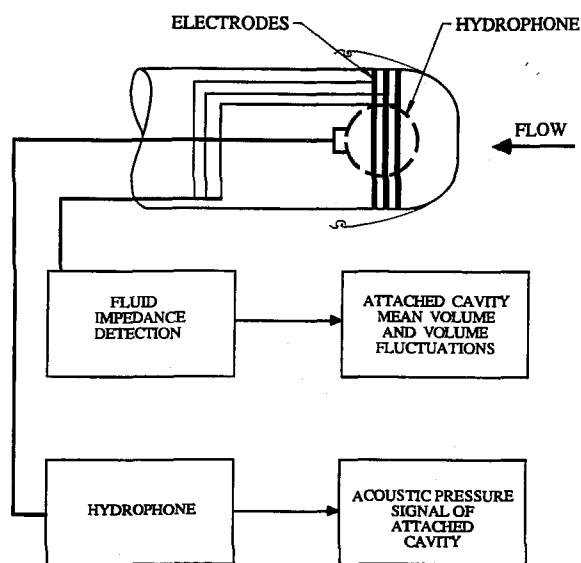


Figure 1 Schematic of Axisymmetric Body Assembly.

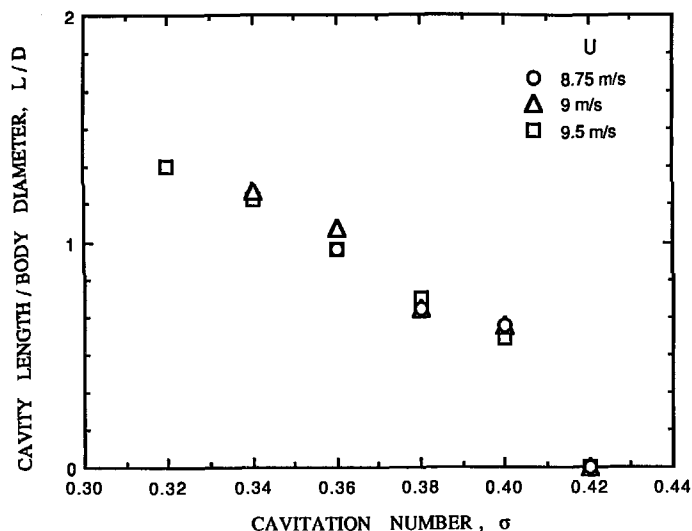


Figure 3 Cavity Length plotted against the Cavitation Number,  $\sigma$ , for various tunnel velocities,  $U$ .

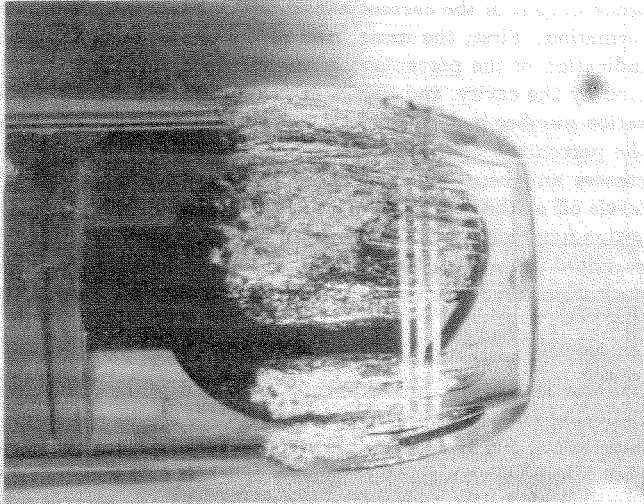
creases. This is the primary signal detected by the electrode system. There may also be a secondary effect due to changes in conductivity of the cavity contents caused by the presence of a liquid and vapor mixture. The dynamic response of the electrode signal processor is on the order of 10 kHz, and the signal to electrical noise ratio was at least 45 dB.

#### 4. Experimental Results

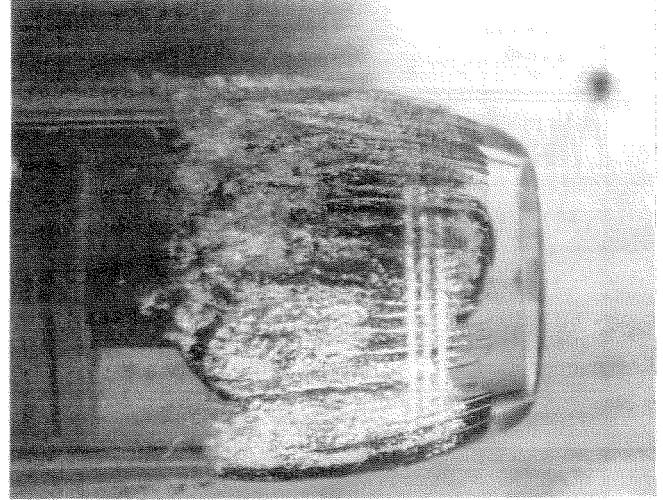
The formation of attached cavities was intermittent and occurred at seemingly random locations on the circumference of the body. Because all the experiments were conducted in a fairly narrow range of Reynolds number ( $Re = 4.4 \times 10^5 - 4.8 \times 10^5$ ), the cavitation formation index for all experiments was about  $\sigma = 0.40$ ; the cavitation was located at about  $s/D = 0.45$ . The attached cavity formation index is defined by the first appearance of *attached* cavitation anywhere on the headform. The cavitation disappearance index, which was always greater than the formation index because of the hysteresis effect, was about  $\sigma = 0.42$ .

The photographs taken at each operating point were used as a reference for the acoustic and electrode data. At first formation the headform circumference was only about half covered with the attached cavities. Portions of the cavity were stable while others were intermittent. As the cavitation number was decreased, the cavities expanded to cover the entire circumference of the body. Further decrease in the cavitation number increased the length of the cavity which is plotted against cavitation number in Fig. 3. The surface of the cavity shows a transition from a smooth laminar interface to a wavy and then a turbulent surface in a manner described and investigated by Brennen [1970]. The point of transition on the cavity surface was about one half of the total cavity length in all cases. The cavity was composed of a series of longitudinal "finger" cavities which, at lower cavitation numbers, combined to cover the entire circumference.

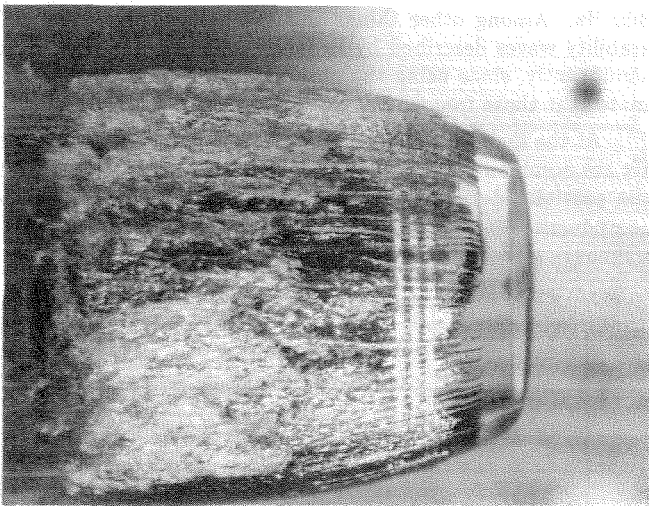
Acoustic spectra of the signal from the internal hydrophone were generated for all operating conditions. The largest portion of the acoustic energy was found in the low frequency range from 0 to 5 kHz where the dominant reverberant modes of the tunnel are located. Hence, the spectra up to 5 kHz are



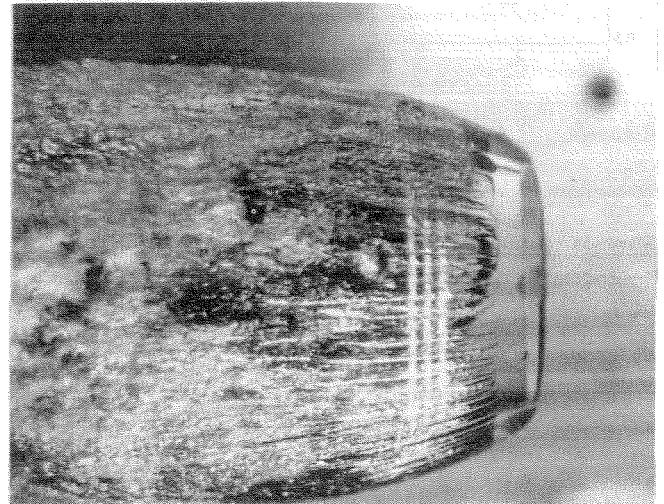
$\sigma = 0.40$



$\sigma = 0.38$



$\sigma = 0.36$



$\sigma = 0.34$

**Figure 2**      Examples of Attached Cavities for  $\sigma = 0.40, 0.38, 0.36$ , and  $0.34$   
at  $U = 9$  m/s.

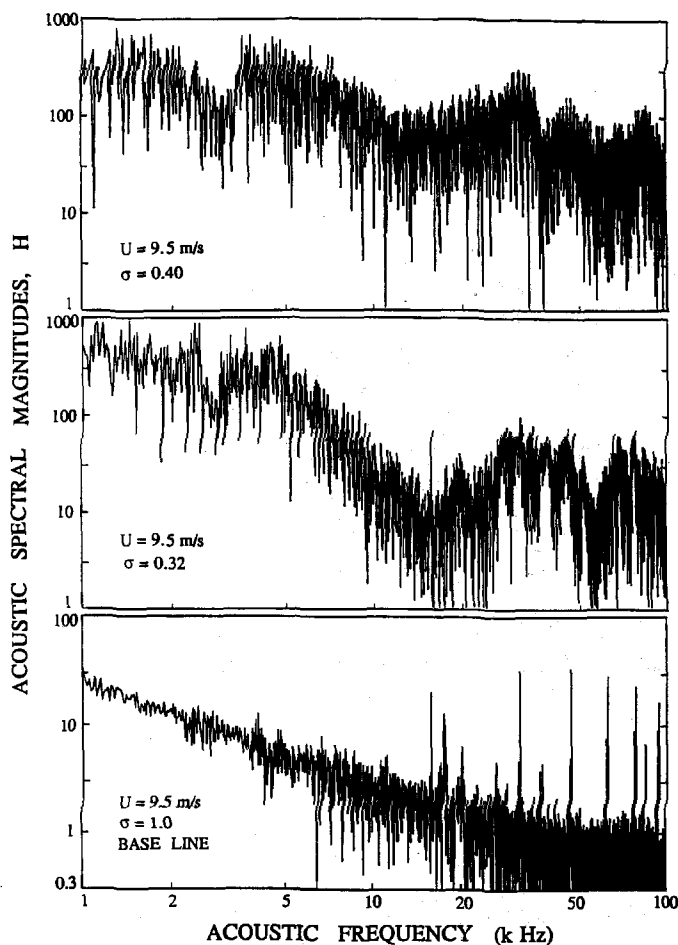


Figure 4 Acoustic Spectra for  $\sigma = 0.40$  and  $0.32$  at  $U = 9.5$  m/s and for  $\sigma = 1.0$  at  $9.5$  m/s. Vertical scale is arbitrary.

of limited value. Fig. 4 presents the spectra for the cavitating conditions of  $\sigma = 0.40$  and  $\sigma = 0.32$  and for the non-cavitating background condition at  $\sigma = 1.0$ , all at a tunnel velocity of  $9.5$  m/s. The background spectra has an approximately  $20$  dB falloff with resonant peaks at higher frequencies. These resonant peaks can be related to specific acoustic path lengths in the water tunnel test section. For  $\sigma = 0.40$  the cavitation was partially developed, and for  $\sigma = 0.32$  the cavity was fully developed. Apart from the background peaks, the cavitating spectra magnitudes are generally at least  $20$ - $40$  dB greater than the background. The cavitation spectra have a similar shape which is significantly different from the background shape, and the magnitudes of the high frequency content for the fully developed cavity are lower than for the partially developed case. This could be due to a muffling effect the cavity may have on the noise reaching the hydrophone. A significant portion of the high frequency noise may be due to the collapse of small bubbles formed in the pressure recovery region where the cavity collapses. In the fully developed case, these bubbles would be further away from the hydrophone and the noise would be somewhat shielded by the cavity. This trend is the reverse of that found by Blake et. al. [1977] for attached cavities on hydrofoils, where lower cavitation numbers led to an increase in

the high frequency magnitudes. The shape of the spectra measured by Blake remains virtually constant with cavitation number, and is similar to his reported background. However, the hydrophone used by Blake was externally mounted and hence the signal detected would be subject to different reverberant or transmission effects than those in the present measurement.

Both the mean and fluctuating components of the electrode output in the current experiment contain interesting information. First, the mean level of the electrode signal is an indication of the percentage of the circumference that is covered by the cavity, and this is presented as a function of cavitation number in Fig. 5. As the cavitation number decreases, the percentage of the circumference covered by the cavity increases and hence the electrode signal voltage increases. It levels off as the cavity becomes fully developed. At high cavitation numbers, the large uncertainty represented by the large standard deviation is due to the temporal intermittency of the cavitation. Once the cavity is fully developed, the uncertainty decreases.

Secondly, the fluctuating component of the electrode signal was analysed. Initial spectra obtained without filtering indicated that there were no frequencies of significant magnitude above  $500$  Hz. Therefore, the fluctuating signal was low pass filtered with a cutoff frequency of  $1$  kHz and was digitally sampled at  $2$  kHz. This filtering eliminated the signals produced by the travelling bubbles which may form on portions of the electrode not covered by the cavity. Fig. 6 represents two typical spectra. They all have a similar shape with large amplitudes at low frequency and a uniform roll off to approximately  $500$  Hz. Among other things this means that the interfacial stability waves described by Brennen [1970] do not contribute significantly, since using the observations of Brennen we estimate that those frequencies are in the range of  $5$ - $10$  kHz.

At the higher cavitation numbers, the frequencies below  $1$  Hz are dominant. The temporal intermittency associated with the partially developed cavities produces this low frequency component. As the cavities become fully developed, these low frequencies become less pronounced. However, an intermedi-

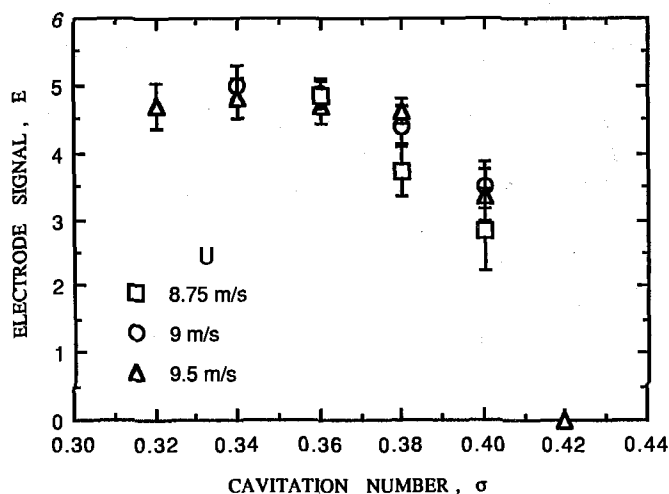


Figure 5 Mean and Standard Deviation of the Electrode Signal,  $E$ , plotted against Cavitation Number. Vertical scale is arbitrary.

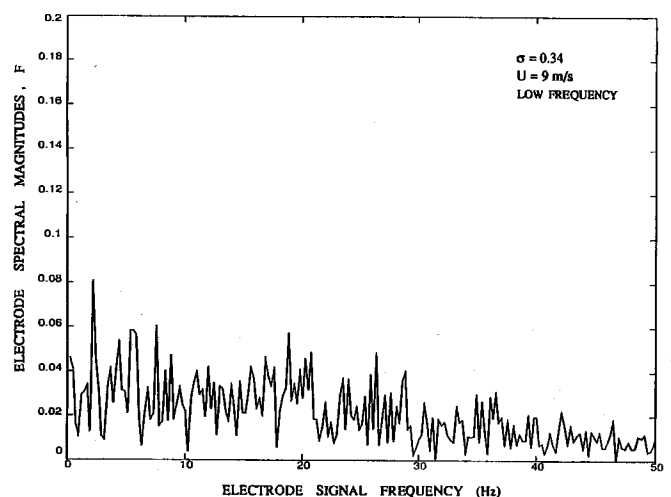
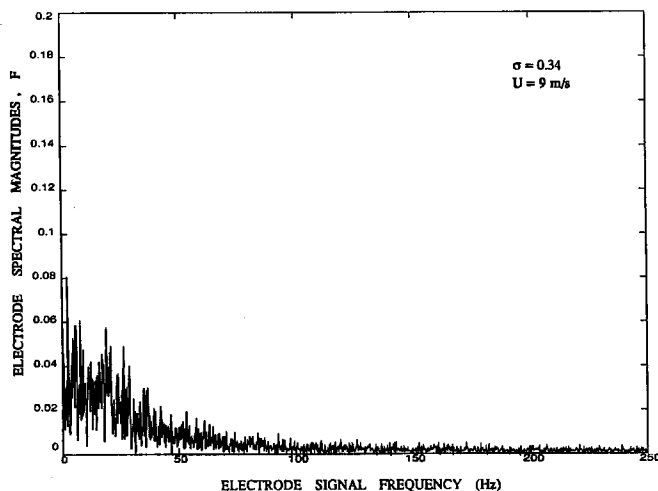
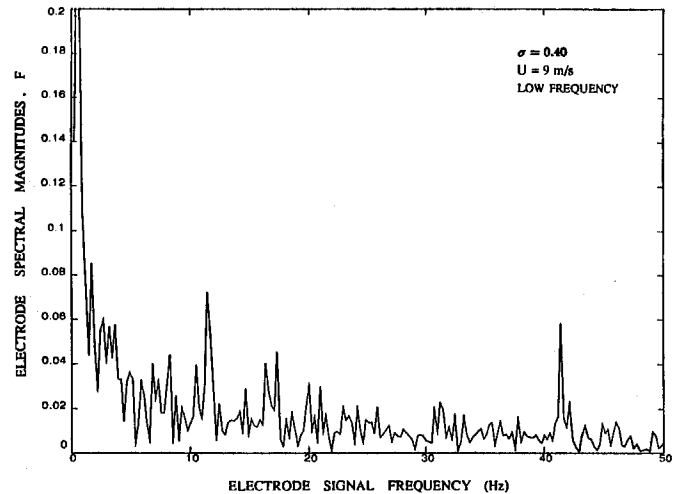
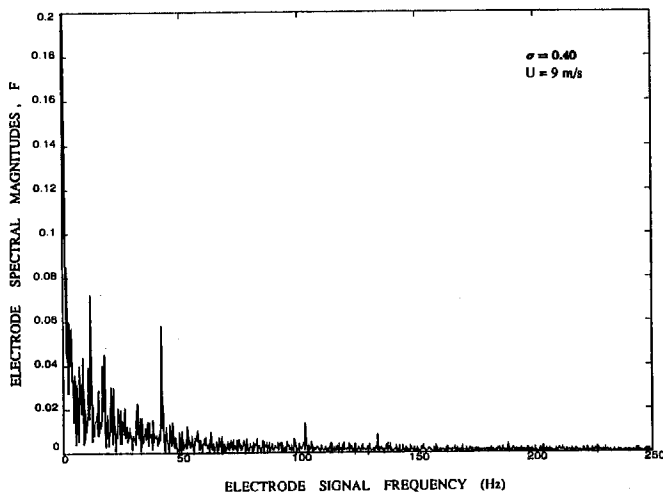


Figure 6 Electrode Signal Spectra for  $\sigma = 0.40$  and  $0.34$  at  $U = 9$  m/s. Vertical scale is arbitrary.

ate frequency oscillation may be found in the spectra for the partially developed cavities. As seen in Fig. 6, the spectra for  $\sigma = 0.40$  has distinct frequency peaks (for example at  $f = 40$  Hz,  $103$  Hz, and  $133$  Hz). These peaks are not due to line noise, are repeatable, and disappear after the cavity becomes fully developed. Since they occur only when the cavity is partially developed, they may be due to pulsation of the finger cavities (see Fig. 7).

After the cavity is fully developed, the mean level of the signal fluctuations has decreased, but it is still significant. Since the electrodes were positioned under the laminar cavity region, where the cavity may be considered evacuated, these fluctuations are mainly due to two processes. Since the fully developed cavity consists of a sum of individual "finger" cavities, the surfaces of the fingers wet the electrode surface, and as these boundaries fluctuate, a signal is generated. Secondly, the cavity surface may intermittently collapse, wetting the surface and producing a signal. These spectra exhibit no dominant frequencies.

## 5. Conclusions

Photographic and acoustic/pressure measurement are the traditional methods used to study attached cavities. Volume

fluctuations are difficult to study acoustically since most of the cavity oscillation frequencies are below  $1$  kHz and are therefore strongly influenced by tunnel reverberation. The hydrophone was placed inside the headform, and the background and cavitating spectra were differentiated. The cavitation noise spectra exhibited a consistent shape, although the magnitudes at

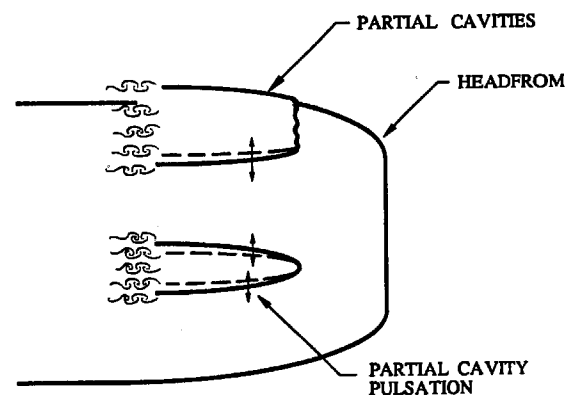


Figure 7 One possible mode of cavity oscillation.

higher frequencies did exhibit some variation with flow conditions.

The electrode technique described here measures the area of surface cavitation as well as any dynamic component which could cause intermittent fluid/surface contact. The fluctuating component of the electrode signal revealed wideband cavity oscillations over a range of frequencies up to 500 Hz. But, in addition and somewhat remarkably, they also showed a series of quite specific and repeatable frequencies present in the dynamic signal produced by intermittent cavities. These frequencies are about 40, 100, and 130 Hz and do not appear to coincide with any other structural or acoustic frequency of the system. They appear to be frequencies associated with pulsation of the finger cavities.

Although only one electrode geometry was used in this experiment, many other geometries are possible. For example, electrodes arrayed along the length of the cavity could yield information concerning the transition process and the collapse and shedding process in the pressure recovery region. We hope to further explore the application of this new technique.

## 6. Acknowledgments

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